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Status of Kilowatt-Class Stirling Power Conversion Using a Pumped NaK Loop for Thermal Input

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Abstract

Free-piston Stirling power conversion has been identified as a viable option for potential Fission Surface Power (FSP) systems on the Moon and Mars. Proposed systems consist of two or more Stirling convertors, in a dual-opposed configuration, coupled to a low-temperature uranium-dioxide-fueled, liquid-metal-cooled reactor. To reduce developmental risks associated with liquid-metal loop integration, a test rig has been built to evaluate the performance of a pair of 1-kW free-piston Stirling convertors using a pumped sodium-potassium (NaK) loop for thermal energy input. Baseline performance maps have been generated at the Glenn Research Center (GRC) for these 1-kW convertors operating with an electric heat source. Each convertor was then retrofitted with a custom-made NaK heater head and integrated into a pumped NaK system at the Marshall Space Flight Center (MSFC). This paper documents baseline testing at GRC as well as the progress made in integrating the Stirling convertors into the pumped NaK loop.

Introduction

Free-piston Stirling power conversion has been identified as a viable option for potential fission surface power (FSP) systems on the Moon and Mars (Refs. 1 to 4). Recent studies have focused on the use of Stirling convertors coupled to a low-temperature (<900 K), uranium-dioxide-fueled, liquid-metal-cooled reactor for potential lunar application in year 2020 (Refs. 2 and 3). The system is considered a low development risk based on the use of terrestrial-derived reactor technology and conventional materials. In addition, all materials and components are compatible with the lunar and Martian environments. Therefore, Mars-based power conversion system designs are expected to be very similar to lunar designs in configuration, set-up, and operations (Ref. 4).

One of the key technical hurdles identified in the development of such a system is the integration of the liquid-metal-pumped loop with a multi-kilowatt Stirling power conversion system (Ref. 4). While earlier Glenn Research Center (GRC) efforts (Ref. 5) have clearly demonstrated the application of liquid metals as a heat transport medium for a Stirling cycle convertor, it is important to note that these heat exchangers utilized two-phase heat pipes in the energy transfer process. The heat transfer characteristics of condensing liquid-metal vapor in heat pipe applications differ substantially from those expected in the single-phase liquid-metal to gas heat exchangers used for heat addition in FSP applications. To reduce developmental risks associated with integrating these liquid-metal to gas heat exchangers into a Stirling power conversion system, a pair of 1-kWe Stirling convertors have been integrated into a pumped NaK loop at the Marshall Space Flight Center (MSFC). The 1-kWe Stirling convertors were built by Sunpower of Athens, Ohio. The performance of these Stirling convertors will be compared with the baseline performance data taken at GRC and described herein. These comparisons will serve as a proof of concept of kilowatt-level Stirling power conversion using single-phase pumped NaK for thermal input.

Baseline Testing

Test Setup

A test rig was built at GRC to measure the baseline performance of these convertors using electric cartridge heaters for thermal input. Testing was conducted in the Stirling Research Laboratory at GRC from March through May 2008. The test rig, shown in Figure 1 and represented schematically in Figure 2, consists of two variacs (one per engine), two free-piston Stirling convertors in a dual-opposed configuration, a cold-end water chiller, a helium fill station, two AC power supplies (used for piston control), and a data acquisition system.

Power is provided to the electrical heating elements through two variacs that receive 208 VAC from the facility power grid. Piston frequency and amplitude, as well as convertor synchronization were controlled using two AC power supplies that apply an AC voltage across the alternator of each convertor. Electric power produced by the alternators was dissipated using 39.7 Ω load resistors. Waste heat was rejected to a circulating water loop that is cooled by a Neslab HX-300 recirculating chiller. Hot-end, cold-end, and alternator housing temperatures, as well as all coolant inlet and exit temperatures were monitored using type-N thermocouples. Cooling water flow rates were measured using turbine flow meters on the cooling supply line. Piston and displacer amplitudes were calculated from Fast Linear Displacement Transducer (FLDT) position sensor measurements.

Figure 1.—The 1-kW dual-opposed Stirling test rig as assembled at GRC.

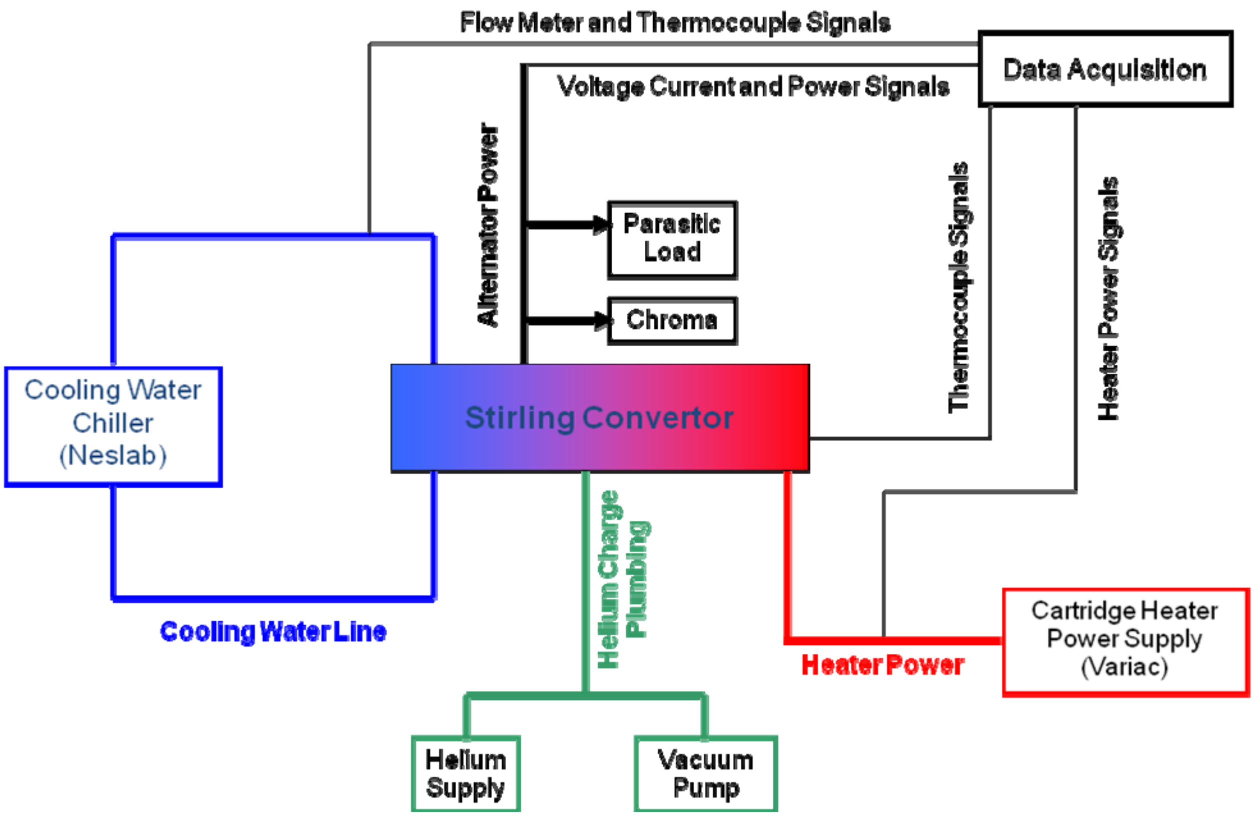

Figure 2.—The 1-kW dual-opposed Stirling test rig schematic.

Method

Baseline performance map testing involved measuring power output and gross thermal efficiency (Ref. 6) of each convertor over a matrix of hot-end and cold-end temperatures and a range of piston amplitudes. These convertors were designed to operate at a charge pressure of 450 psia, a hot-end temperature of 550 °C, and a cold-end temperature of 50 °C, at a piston amplitude of 10 mm. During performance map testing, the convertor hot-end temperature was varied between 400 and 550 °C, in increments of 50 °C, at cold-end temperatures of 30, 40, 50, and 70 °C. At the design hot-end and cold-end temperatures, the intended power piston amplitude test range was 6 to 11 mm (1 mm increments). At all other hot-end and cold-end temperatures, the intended power piston amplitude test range was 9 to 11 mm (1 mm increments).

Constraints on the maximum voltage across the cartridge heaters limited the maximum piston amplitude to 10.5 mm during 550 °C hot-end tests. Constraints on the minimum power factor limited the maximum piston amplitude to 9 mm during all 30 °C cold-end tests. This constraint also limited maximum piston amplitude to 9 mm during 40 °C cold-end tests at hot-end temperatures of 400 and 450 °C. For all tests in which power factor constraints prevented the acquisition of data beyond a 9 mm piston amplitude, data was acquired at a piston amplitude of 8 mm to expand the data range.

Results

Each datapoint shown in the performance maps shown in Figures 3 and 4 is the average of 30 measurements taken at ten-second intervals over a 5-min period. Each 5-min period began when the alternator gas temperature (the last temperature to reach steady-state) changed at a rate of no more than 1 °C over a 5-min period. Manufacturer's data shows that the actual cold-end temperature can be 2 to 6 °C warmer than the cooling water temperature. The cold-end temperatures reported are estimated from correlations based on manufacturer's data, *not* the cooling water temperature. The legends shown in Figures 3 and 4 indicate the hot and cold-end temperatures of the convertors in °C.

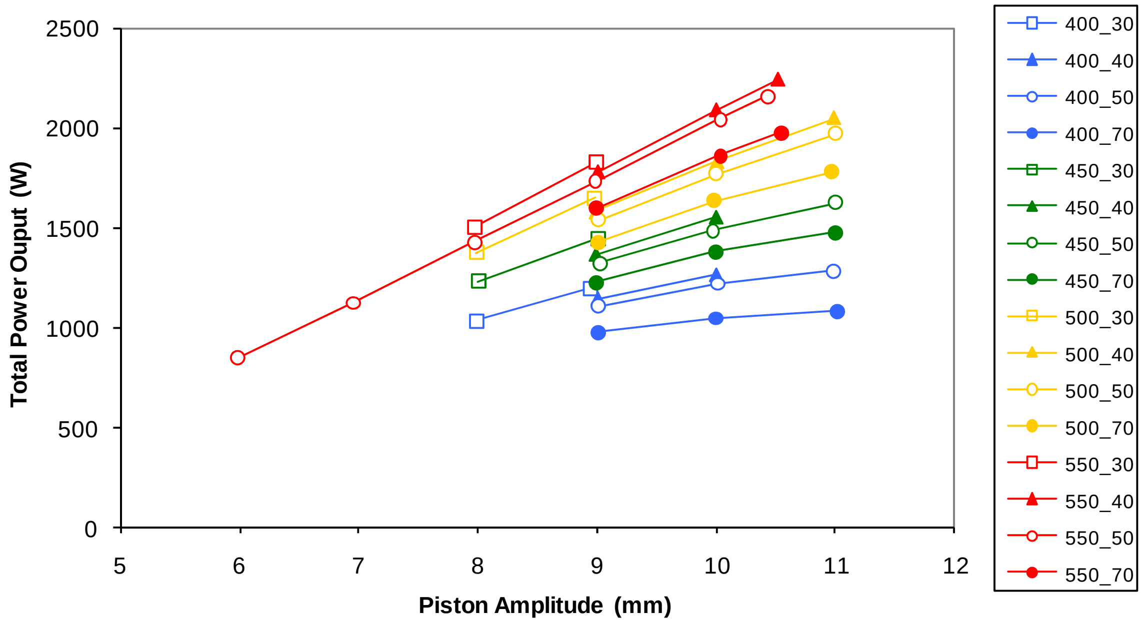

Figure 3.—Total power output versus piston amplitude at various operating conditions.

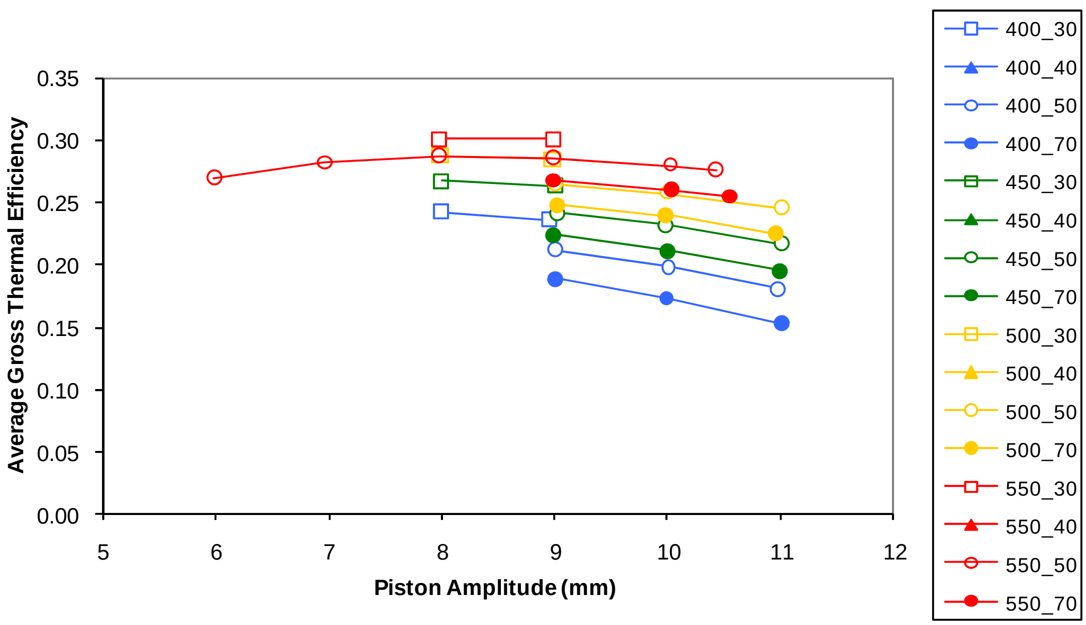

Figure 4.—Average convertor efficiency versus piston amplitude at various operating conditions.

The total power output is the sum of the individual power output of each convertor, and is shown in Figure 3 at various operating conditions. As expected, the total power output increases with both increasing temperature ratio and increasing piston amplitude. The maximum total power of 2240 W_e was produced at a 550 °C hot-end, 40 °C cold-end temperature with a piston amplitude of 10.5 mm. This power level was achieved at a system gross thermal efficiency of 28.6 percent. At this operating point, the maximum piston amplitude of 11 mm could not be achieved because of the constraints on maximum voltage across the electric resistance heaters described above.

The ratio of the total electrical power output of both convertors to the total electrical input to the cartridge heaters is defined as the gross thermal efficiency (Ref. 6) and is plotted in Figure 4 at various operating conditions. As expected, the gross thermal efficiency increases with increasing temperature ratio. For a given set of hot-end and cold-end temperatures, the maximum gross thermal efficiency occurs between 8 and 9 mm piston amplitude. The maximum gross thermal efficiency declines at piston amplitudes above 9 mm most likely due to heater head heat transfer limitations at the higher piston amplitudes. In the cases where the temperature ratio is approximately equal (i.e., 500 °C hot-end/50 °C cold-end and 550 °C hot-end/70 °C cold-end) the efficiency versus piston amplitude curves are very similar. The maximum gross thermal efficiency of 30.0 percent was achieved at operating temperatures of 550 °C hot-end, and 30 °C cold-end and a piston amplitude of 9 mm. At this operating point, the total power was 1820 W_e.

Current Convertor Configuration

Heater Head Modification

The design process for the NaK heater heads began with considering several fluid housing geometries. The desire to have a uniform fluid flow while minimizing circumferential temperature distribution led to the geometry shown in Figure 5. A more detailed discussion of candidate geometries and the selection process was reported by Dyson (2008) (Ref. 7). The chosen design consists of an inlet plenum in which NaK impinges on the dome of the hot end of the Stirling convertor, then flows axially across the Stirling acceptor region before accumulating in a torus, which drains the NaK outlet. Once this general geometry was selected, a more detailed fluid flow and structural analysis was performed. The key design parameters of the NaK heater head are: (1) capable of transferring approximately 4500 W of thermal energy into the Stirling convertor, (2) NaK inlet temperature of 825 K, (3) designed for optimal performance at a NaK flow rate of 0.55 kg/s, (4) NaK velocities are below 1 m/s, and (5) the pressure drop between the inlet and outlet is less than 1 psi.

The region of interest, structurally, is the weld which attaches the NaK head to the Stirling convertor. Detailed finite element analysis, focused on this region, was conducted to verify that this weld will maintain structural integrity throughout testing, taking into account rupture, fatigue, and creep.

Fabrication of the NaK heater heads and assembly of the heads onto the Stirling convertors offered unique challenges to the manufacturing community. Welding components to finished goods was difficult. The challenge was further complicated by the need to limit distortions to thousandths of an inch on high value hardware. As a resolution to these issues, a micro TIG (tungsten inert gas) welding technique was selected. The final head had minimal distortion (0.002 in.) and passed dye penetration, hydro, and helium leak tests.

NaK Loop Integration

Following fabrication and integration of the NaK heater heads onto the Stirling convertor, the modified 1-kW convertors were installed in a pumped NaK loop test facility at MSFC. This loop consists of an upper and lower reservoir to accommodate NaK expansion during heating, a custom built Annular Linear Induction Pump (ALIP), an electrically powered NaK heater, a gas cooler, and a custom flow meter. The Stirling convertors were plumbed in immediately downstream of the NaK heater and upstream of the gas cooler. A more complete description of the NaK loop is described by Garber (2008) (Ref. 8). Figure 6 shows the Stirling convertors as installed at MSFC.

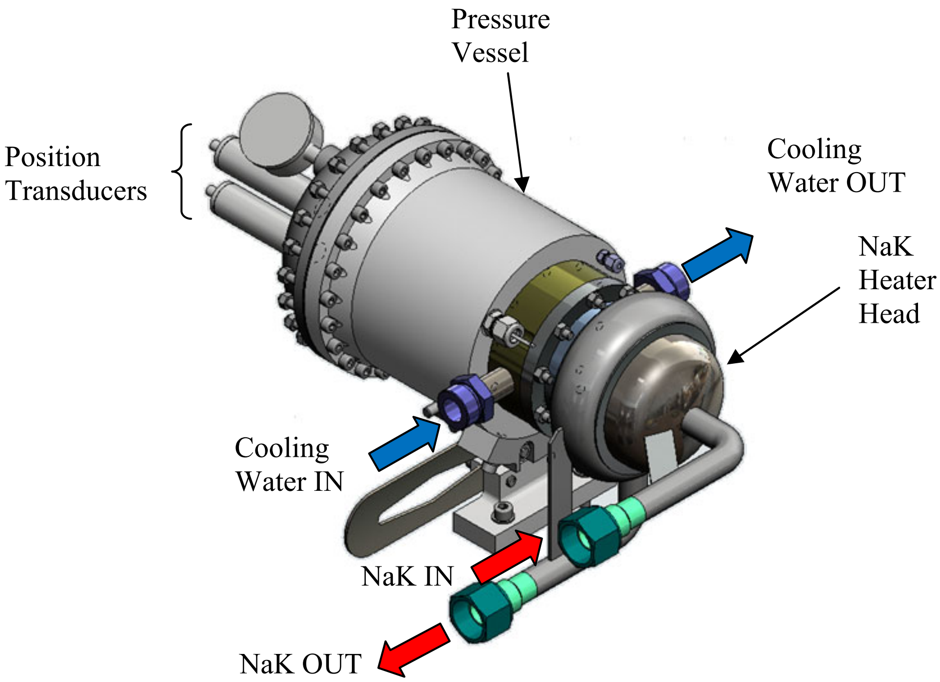

Figure 5.—NaK heater head installed on 1-kWe Stirling power convertor.

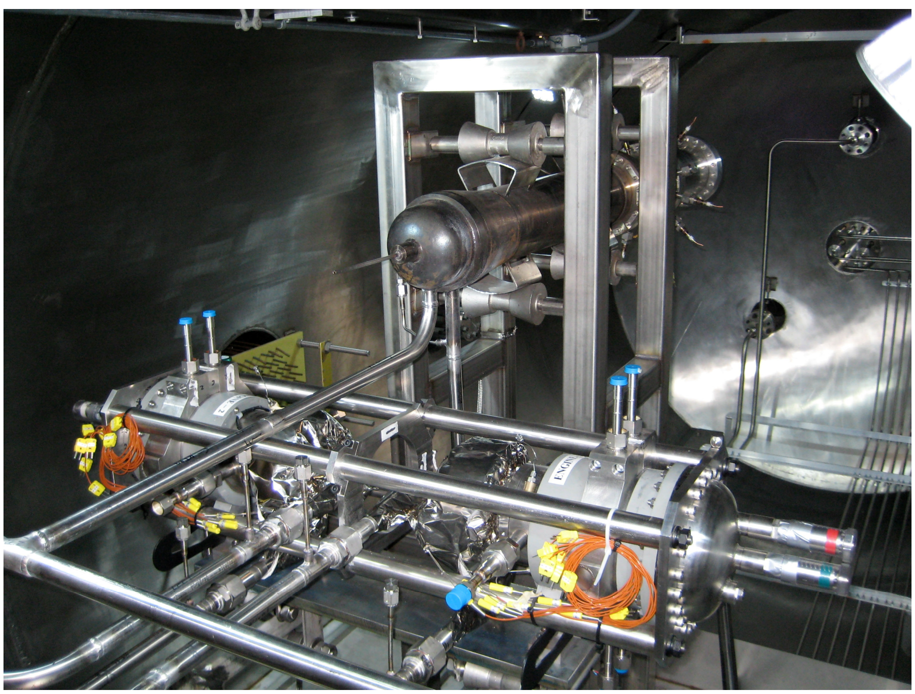

Figure 6.—Stirling convertors as installed in the MSFC pumped NaK loop test facility.

Conclusion

A baseline performance map has been established for a pair of 1-kW Stirling convertors that used electrical resistance heating elements for thermal input. The electrical resistance heating elements used during the baseline tests have been replaced with NaK-compatible heater heads and the convertors have been integrated into the pumped-NaK loop at the Marshall Space Flight Center. Comparison between the current test data and data to be taken using a NaK pumped loop for thermal input, will provide valuable information about NaK heater head design and overall power conversion unit design. This information will be crucial to the development of free-piston Stirling technology for use in fission surface power applications.

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14. ABSTRACT
Free-piston Stirling power conversion has been identified as a viable option for potential Fission Surface Power (FSP) systems on the Moon and Mars. Proposed systems consist of two or more Stirling convertors, in a dual-opposed configuration, coupled to a low-temperature uranium-dioxide-fueled, liquid-metal-cooled reactor. To reduce developmental risks associated with liquid-metal loop integration, a test rig has been built to evaluate the performance of a pair of 1-kW free-piston Stirling convertors using a pumped sodium-potassium (NaK) loop for thermal energy input. Baseline performance maps have been generated at the Glenn Research Center (GRC) for these 1-kW convertors operating with an electric heat source. Each convertor was then retrofitted with a custom-made NaK heater head and integrated into a pumped NaK system at the Marshall Space Flight Center (MSFC). This paper documents baseline testing at GRC as well as the progress made in integrating the Stirling convertors into the pumped NaK loop.

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